

UNCLASSIFIED  
AD 430599

DEFENSE DOCUMENTATION CENTER  
FOR  
SCIENTIFIC AND TECHNICAL INFORMATION  
CAMERON STATION, ALEXANDRIA, VIRGINIA



UNCLASSIFIED

NOTICE: When government or other drawings, specifications or other data are used for any purpose other than in connection with a definitely related government procurement operation, the U. S. Government thereby incurs no responsibility, nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use or sell any patented invention that may in any way be related thereto.

430599

CATALOGUED BY DDC  
AS AD 113

430599

*AeroChem***Research Laboratories, Inc.**

a subsidiary of PFAUDLER PERMUTIT, INC.

P. O. BOX 12, PRINCETON, N. J.  
PHONE: WALnut 1-7070

TP-83

February 18, 1964

Dissociating Gases as Natural Convection Coolants<sup>1</sup>DANIEL E. ROSNER<sup>2</sup>Introduction

The use of liquids near their critical point has been investigated by F. Schmidt [1] for cooling turbine blades by natural convection. This method takes advantage of (i) buoyancy induced-convection currents due to the very large accelerations associated with turbine blade rotation, and (ii) the augmented thermal expansion coefficient and thermal conductivity of liquids near their critical point. Now, it is also known that the thermal dissociation of polyatomic gases greatly increases their expansion coefficient [2] and thermal conductivity [3-6]. It therefore seems relevant to inquire as to whether equilibrium dissociating gases might not offer some advantages in natural convection cooling applications.<sup>3</sup> For example, in the

<sup>1</sup>This work was supported in part by The Allison Division of General Motors Corporation under Purchase Order G808789 and The Air Force Office of Scientific Research, Propulsion Division of The Office of Aerospace Research, under Contract AF 49(638)-1138; Prepared for submission as a Technical Brief, to The ASME Transactions, Series C, Journal of Heat Transfer.

<sup>2</sup>Aeronautical Research Scientist

<sup>3</sup>The only available theoretical study of natural convection in a dissociating gas appears to be that of Scheller and Dryden [7]. In the present note the feasibility of this basic scheme is briefly investigated for this class of coolants in, for example, rotating machinery.

case of a turbine one might ask whether comparable cooling effects can be achieved with less total mass of coolant in the blade, thereby reducing centrifugal stress levels. Our purpose here then is to present and illustrate a method to examine the possible merits of equilibrium dissociating gases for this general class of natural convection cooling applications.

#### Conventional Natural Convection Cooling Systems

A typical physical configuration envisioned here is shown in Fig. 1. The coolant is confined in one or more holes drilled (in the spanwise direction) in each turbine blade and closed at the outer end. The centrifugal acceleration,  $a$ , for such blading is of the order of  $10^7$  to  $10^8$  cm/sec<sup>2</sup> and is thus some  $10^4$  to  $10^5$  times greater than the gravitational acceleration,  $g$ .

In the presence of temperature gradients produced by contact with the convectively heated blade material, the coolant expands and experiences a large body force directed toward the blade root. Heat is removed at this location by a separate cooling system and the heavier (coolant) medium now experiences a body force driving it centrally toward the blade tip. Being closed at this end, the fluid is then heated once again, turns the corner and repeats the cycle. In the thin thermal boundary layer limit<sup>4</sup> attainable heat transfer coefficients have been estimated by Schmidt [1] for the case of water as the coolant by invoking a correlation formula of the Nusselt type  $Nu = Nu(Gr, Pr)$ , developed from observations of heated vertical plates in air. Here  $Gr$  is the familiar Grashof number, defined by

$$Gr \equiv a \beta \cdot \Delta T \cdot x^3 / \nu^2 \quad (1)$$

---

<sup>4</sup>i. e., non-interacting boundary layers, small curvature effects.

where  $a$  is the effective acceleration,  $\beta$  is the thermal expansion coefficient of the fluid,  $\Delta T$  is the imposed temperature difference,  $x$  is the distance from the origin of the thermal boundary layer, and  $\nu$  is the kinematic viscosity. As pointed out by Ellerbrock [8] Grashof numbers in the holes of free convection turbines based on the length of the holes ( $x = L$ ) are in the approximate range  $10^{10}$  to  $10^{15}$ . Since transition to turbulence is ordinarily associated with values of  $Gr \cdot Pr$  of the order of  $10^9$  (the so-called critical Rayleigh number,  $Ra_{crit}$ ) this indicates that in these applications the boundary layers must be turbulent. Hence, the correlation formula suggested by Eckert and Jackson [9] would be appropriate,<sup>5</sup> viz.

$$\overline{Nu} = 2.46 \times 10^{-2} (Gr)^{2/5} (Pr)^{7/15} \left[ 1 + 0.494 (Pr)^{2/3} \right]^{-2/5} \quad (2)$$

Equation (2) is expected to be most accurate for Prandtl numbers of order unity, if the property variations across the boundary layer are small. In a variable property situation reasonable predictions are possible if one introduces all property values evaluated at a reference temperature about midway<sup>6</sup> between the highest and lowest temperatures appearing in the system.

If in this class of applications one is interested in ranking fluids as to their ability to transfer heat at high rates in a system of prescribed  $a$ ,  $L$ ,  $\Delta T$ , then Eq. (2) indicates that the relevant property group to consider is

$$\overline{q}_{ref} \equiv 2.46 \times 10^{-2} \lambda \left( \frac{g\beta}{\nu^2} \right)^{2/5} \left( \frac{\nu}{a} \right)^{7/15} \left[ 1 + 0.494 \left( \frac{\nu}{a} \right)^{2/3} \right]^{-2/5} \quad (3)$$

<sup>5</sup>The exponent of the Prandtl number is erroneously given as  $7/5$  in the second edition of Ref. 10.

<sup>6</sup>Actually, the work of Sparrow quoted in Ref. 10 indicates that  $T_*$  should be chosen somewhat closer to the hot-side temperature.

which may be regarded as a reference heat flux, i. e., the heat flux pertaining to an acceleration of one g, unit length and unit  $\Delta T$ , in any consistent set of units.<sup>7</sup> It is therefore of interest to compute values of this group over the temperature and pressure range of interest, for both liquids and gases, with and without chemical reaction. Some initial results of this type will be discussed below.

#### Effect of Dissociation on the Thermal Conductivity and Expansion Coefficient of Gases

According to the simple kinetic theory of ideal, inert, gases:  $\lambda \propto T^{1/2}$ ,  $\beta \propto T^{-1}$ ,  $\nu \propto T^{3/2}p^{-1}$  and  $\alpha \propto T^{3/2}p^{-1}$ , so that for such gases one expects the approximate behavior

$$\bar{q}_{\text{ref}}'' \propto p^{4/5} T^{-11/10} \quad (4)$$

Therefore  $\bar{q}_{\text{ref}}''$  will ordinarily be largest at high pressures<sup>8</sup> and low temperatures, being almost directly proportional to the density. However, for gases which dissociate (e.g.,  $\text{H}_2 \rightarrow 2\text{H}$ ,  $\text{N}_2\text{O}_4 \rightarrow 2\text{NO}_2$ ,  $\text{Cl}_2 \rightarrow 2\text{Cl}$ ,  $2\text{HI} \rightarrow \text{H}_2 + \text{I}_2$ ,  $(\text{HF})_6 \rightarrow 6\text{HF}$ ) large departures from this simple behavior are known to occur. This is particularly true in the case of the heat conductivity  $\lambda$  and expansion coefficient  $\beta$ . By comparison, dissociation introduces relatively small changes in the kinematic viscosity  $\nu$ , thermal diffusivity,  $\alpha$ , and, hence the Prandtl number  $\text{Pr} \equiv \nu/\alpha$ . A rough estimate of the thermochemical augmentation in  $\bar{q}_{\text{ref}}''$  is then provided by the simple approximate

---

<sup>7</sup>Alternatively,  $\bar{q}_{\text{ref}}''$  may be regarded as the average heat transfer coefficient for a configuration with unit length and unit temperature difference.

<sup>8</sup>Stress considerations will, of course, set an upper limit on the allowable internal pressure. Calculations below have not been made for pressures above  $10^2$  atm.

TP-83

result

$$\frac{\bar{q}_{\text{ref, dissociation}}''}{\bar{q}_{\text{ref, inert}}''} \approx \left( \frac{\lambda_{\text{eq}}}{\lambda_f} \right) \left( \frac{\beta_{\text{eq}}}{\beta_f} \right)^{2/5} \quad (5)$$

For example, consider Figs. 2 and 3, which were prepared for the case of equilibrium dissociating hydrogen [5, 6]. At  $p = 0.1$  atm,  $\lambda_{\text{eq}}/\lambda_f \approx 9.5$  and  $\beta_{\text{eq}}/\beta_f \approx 3.1$  so that  $\bar{q}_{\text{ref, eq}}''/\bar{q}_{\text{ref, f}}'' \approx 15$  at a temperature level of about  $3250^\circ\text{K}$ . At  $p = 1$  atm,  $\lambda_{\text{eq}}/\lambda_f \approx 7.5$ ,  $\beta_{\text{eq}}/\beta_f \approx 2.8$  so that  $\bar{q}_{\text{ref, eq}}''/\bar{q}_{\text{ref, f}}'' \approx 11$  at a temperature level of  $3750^\circ\text{K}$ . Thus, dissociation can increase the reference heat flux by more than one order of magnitude, with the greatest augmentation being realized at low pressures. Of course the temperature level at which these large effects occur (for any specified pressure) will depend on the strength of the chemical bond being broken. Indeed it can be shown that for any dissociating diatomic gas the maximum enhancement will occur at the temperature at which the degree of dissociation,  $\alpha_{\text{eq}}$ , is near 0.50. In terms of the equilibrium constant  $K_p(T)$ , this will occur at the "optimum" temperature  $T_{\text{opt}}$  defined implicitly by  $K_p(T_{\text{opt}}) \approx (4/3)p$ . Conversely, if one desires operation at some prescribed temperature level  $T$  then the maximum advantage of dissociation will be realized at the pressure level  $p_{\text{opt}} \approx (3/4) K_p(T)$ . In the light of this background information and the detailed data given in Refs. 3, 4, 11, and 12, one can now compute the "figure of merit"  $\bar{q}_{\text{ref}}''$  for various coolants, over a range of pressures and temperatures.

#### Relative Effectiveness of Dissociating Gases as Heat Transfer Media in the Turbulent Natural Convection Regime

Values of  $\bar{q}_{\text{ref}}''$  defined by Eq. (3) are shown plotted in Fig. 4 over the temperature range  $300^\circ\text{K} < T < 5000^\circ\text{K}$  for the particular dissociating gases  $\text{H}_2$ ,  $\text{N}_2\text{O}_4$  and air.

# TF-89

For both  $H_2$  and  $N_2O_4$  the expansion coefficient was computed from chemical contribution,  $C_{p, chem}$ , to the molar heat capacity, with the help of the relation [5]

$$\beta = \frac{1}{T} \left[ 1 + \frac{(C_{p, chem}/R)}{(\Delta H/RT)} \right] \quad (6)$$

Relevant data was obtained from Refs. 11, 3, 4, and 12, respectively. For dissociating air, use was made of the compressibility,  $Z$ , tabulated by Hansen [12], together with the relation

$$\beta = \frac{1}{T} \left[ 1 + \left( \frac{\partial \ln Z}{\partial \ln T} \right)_{p = \text{const}} \right] \quad (7)$$

derived from the definitions of  $\beta$  and  $Z$ . The trends anticipated in the discussion of the previous section are borne out (cf. Fig. 4). In particular, it is interesting to note that at  $p = 1$  atm and  $T = 300^\circ K$ , dissociating nitrogen tetroxide outperforms either air or hydrogen by more than one order of magnitude on a heat flux basis. Also, as expected, both hydrogen and air exhibit their maximum thermochemical contribution at much higher temperature levels, reflecting the higher strengths of the bonds being broken [ $H_2$ , (103 Kcal/mole),  $O_2$  (118 Kcal/mole) and  $N_2$  (225 Kcal/mole) as compared with  $N_2O_4$  ( $\sim 14$  Kcal/mole)]. While data for  $N_2O_4$  at higher pressures was not readily available, it appears that  $N_2O_4$  could be used to obtain values of  $\bar{q}_{ref}''$  larger than  $10^{-3} \text{ cal}(\text{cm})^{-2}(\text{sec})^{-1}$  at pressures less than  $10^2$  atm. However, it is also clear from Fig. 4 that liquids outperform pressurized dissociating gases on a heat flux basis (cf. data [10] for saturated  $Hg$ ,  $NH_3$  and  $H_2O$ ). However, additional data is required at higher temperature levels, and the role of stress limitations in properly assessing the relative merits of liquid coolants



in a particular application remain to be investigated. It would also be of interest to consider saturated vapor/liquid mixtures in this regard, with some attention paid to cases in which the vapor dissociates [13]. Finally, additional study of phenomena near the critical point is necessary.

#### Required Values of the Reference Heat Flux

An estimate of the value of  $\bar{q}_{\text{ref}}''$  required in any particular case can be obtained on the basis of the following illustrative heat balance considerations. Suppose it is desired to have a turbine blade operate at a temperature  $\Delta T_g$  below the turbine inlet gas total temperature. Then, if  $\bar{h}_g$  is the mean heat transfer coefficient for the outer area,  $A_o$ , of the entire blade, the total forced convective heat transfer rate will be

$$\dot{Q} = \bar{h}_g A_o \cdot \Delta T_g \quad (8)$$

In the steady state,  $\dot{Q}$  must be equal to the net rate of heat transfer by natural convection inside the blade where the wetted area is  $A_i$ . Using the definition of  $\bar{q}_{\text{ref}}''$  this may be written

$$\dot{Q} = \bar{q}_{\text{ref}}'' A_i \left[ \left( \frac{\Delta T}{\Delta T_{\text{ref}}} \right)^{7/5} \left( \frac{a}{g} \right)^{2/5} \left( \frac{L}{L_{\text{ref}}} \right)^{1/5} \right] \quad (9)$$

where, as noted earlier, we have adopted  $\Delta T_{\text{ref}} \equiv 1^\circ\text{K}$ ,  $L_{\text{ref}} \equiv 1 \text{ cm}$ . Combining Eqs. (8) and (9) gives the immediate result

$$\bar{q}_{\text{ref}}'' = \bar{h}_g \Delta T_g \left[ \left( A_o/A_i \right) \left( \Delta T/\Delta T_{\text{ref}} \right)^{-7/5} (a/g)^{-2/5} \left( L/L_{\text{ref}} \right)^{-1/5} \right] \quad (10)$$

TP-83

For example, consider a case for which  $L = 5 \text{ cm}$ ,  $\bar{h}_g = 10^{-1} \text{ cal}(\text{cm})^{-2}(\text{sec})^{-1}(\text{K})^{-1}$ ,  $A_o/A_i = 2$ , and  $a/g = 10^5$ . Then, if one desires a cooling effect of  $\Delta T_g \approx 300^\circ\text{K}$  and one can maintain the blade root at a temperature such that  $\Delta T \approx \Delta T_g$  one finds that  $\bar{q}_{\text{ref}}''$  must be of the order of  $10^{-4} \text{ cal}(\text{cm})^{-2}(\text{sec})^{-1}$ . As suggested by Fig. 4, values of this order of magnitude can be achieved with dissociating gases at internal pressures below  $10^2 \text{ atm}$ .

### Conclusions

On the basis of the considerations outlined above the following conclusions have been drawn:

- a. Molecular dissociation increases the effectiveness of gases as natural convection heat transfer media largely by virtue of the attendant increase in thermal expansion coefficient  $\beta$  and thermal conductivity  $\lambda$ , with the latter effect being the more important (cf. Eq. 5). Consequently, in temperature limited systems an optimum pressure level, strongly dependent on the strength of the bond being broken, will exist for maximum coolant effectiveness.
- b. Coolants in the dissociation region can be ranked in accord with a figure of merit derived from the thermophysical property groupings which enter the expression for the relevant convective heat transfer coefficient (cf. Eq. 3).
- c. Fully enclosed, pressurized dissociating gases may be capable of transferring heat away from turbomachinery components at rates sufficient to enable the use of higher inlet total temperatures. Even at 1 atm, 1g and temperatures not far from  $300^\circ\text{K}$ , easily dissociated gaseous coolants can be found which are more than ten times as effective as air.
- d. A simple ranking technique of the type presented can be used to show when dissociating gases are competitive for a given natural convection cooling application and, hence, when more accurate boundary layer calculations or experiments are

required. As already indicated, very few accurate natural convection solutions for dissociating gases have been reported in the open literature to date.

# References

- <sup>1</sup>F. H. W. Schmidt, "Heat Transmission by Natural Convection at High Centrifugal Acceleration in Water-Cooled Gas Turbine Blades," IME-ASME General Discussion on Heat Transfer, Inst. Mech. Eng., London, 1951, pp. 161-163.
- <sup>2</sup>S. S. T. Fan and D. M. Mason, "Effects of Chemical Reactions on Gas Properties and Lewis Numbers," ARS Journal, vol. 32, 1962, p. 899.
- <sup>3</sup>R. S. Brokaw, "Correlation of Turbulent Heat Transfer in a Tube for the Dissociating System  $N_2O_4 \rightleftharpoons 2NO_2$ ," NACA RM E57K19a, March 1958.
- <sup>4</sup>K. P. Coffin and C. O' Neal, Jr., "Experimental Thermal Conductivities of the  $N_2O_4 \rightleftharpoons 2NO_2$  System," NACA TN 4209, February 1958.
- <sup>5</sup>D. E. Rosner, "Properties of Equilibrium Dissociating Hydrogen for Predicting Convective Heating in Nuclear-Thermal Rockets," AeroChem TP-27, DDC AD 257-863, March 1961; Errata and Addenda, 23 October 1961.
- <sup>6</sup>D. E. Rosner, "Reflections on the Role of Chemical Dissociation and Recombination in the Determination of Gas Properties and Convective Heat Transfer," AeroChem TP-38, NASA Abstract N62-17479, January 1962.
- <sup>7</sup>K. Scheller and C. E. Dryden, "Free Convection Heat Transfer in a Reacting Gas Enclosed Between Parallel Vertical Plates," Chemical Engineering Progress Symposium Series, No. 59, No. 41, pp. 208-220.
- <sup>8</sup>H. Ellerbrock, "Some NACA Investigations of Heat Transfer of Cooled Gas-Turbine Blades," IME-ASME General Discussion on Heat Transfer, Inst. Mech. Eng., London, 1951, pp. 410-420.
- <sup>9</sup>E. R. G. Eckert and T. Jackson, "Analysis of Turbulent Free-Convection Boundary Layer on Flat Plate," NACA TN 2207, 1950.
- <sup>10</sup>E. R. G. Eckert and R. M. Drake, Jr., Heat and Mass Transfer, McGraw Hill, Second Edition, 1959.
- <sup>11</sup>N. T. Grier, "Calculation of Transport Properties and Heat-Transfer Parameters of Dissociating Hydrogen," NASA TN-D-1406, October 1962.
- <sup>12</sup>C. F. Hansen, "Approximations for the Thermodynamic and Transport Properties of High-Temperature Air," NASA TR R-50, 1959.
- <sup>13</sup>P. Gray, "Heat Capacity of Saturated Dissociating Vapors and the Form of Their Saturation Vapor Pressure Curves," Progress in International Research on Thermodynamic and Transport Properties, Academic Press, No. 7, 1962, pp. 100-106.

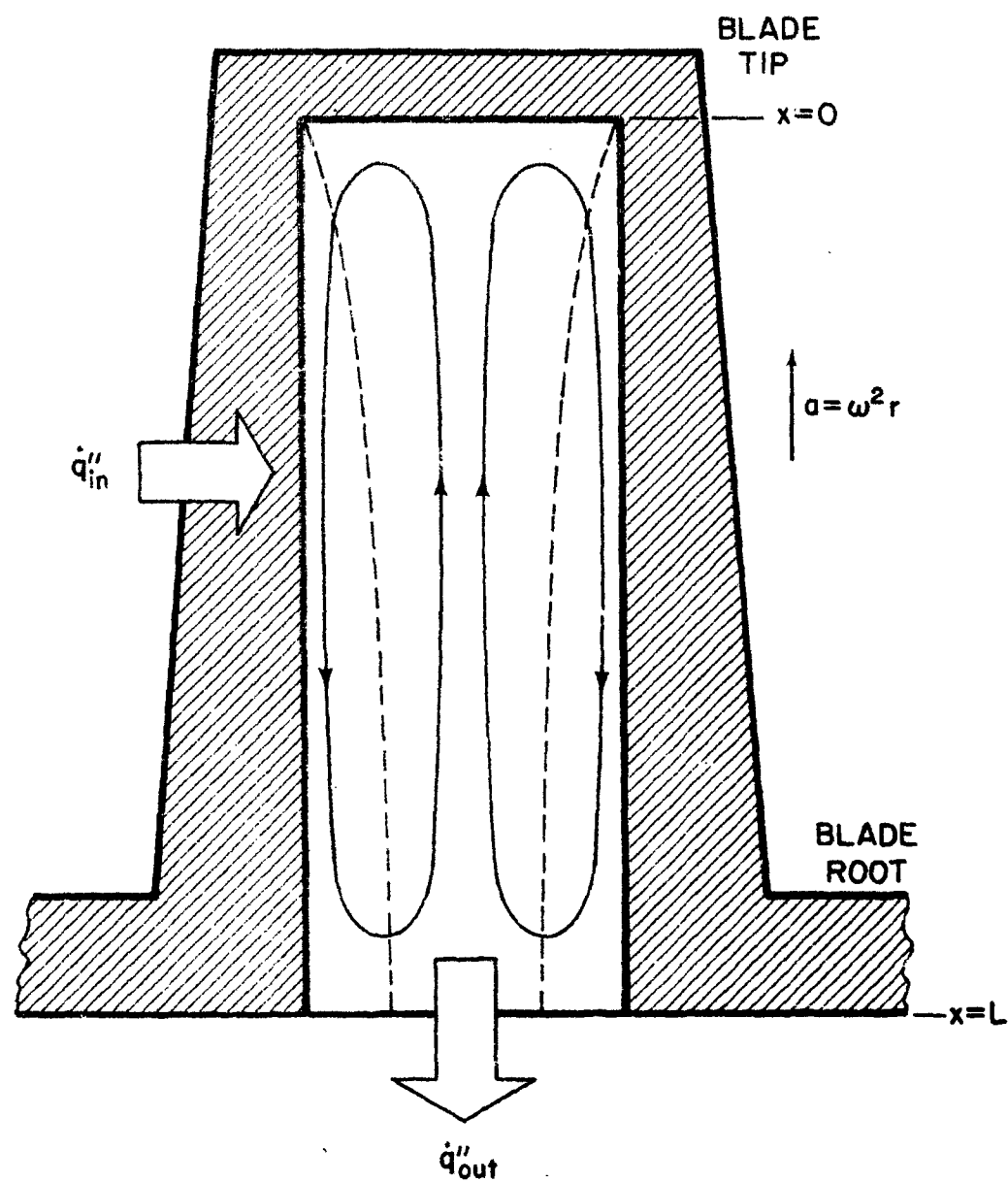


FIG. 1 SCHEMATIC OF A NATURAL CONVECTION COOLED GAS TURBINE ROTOR BLADE

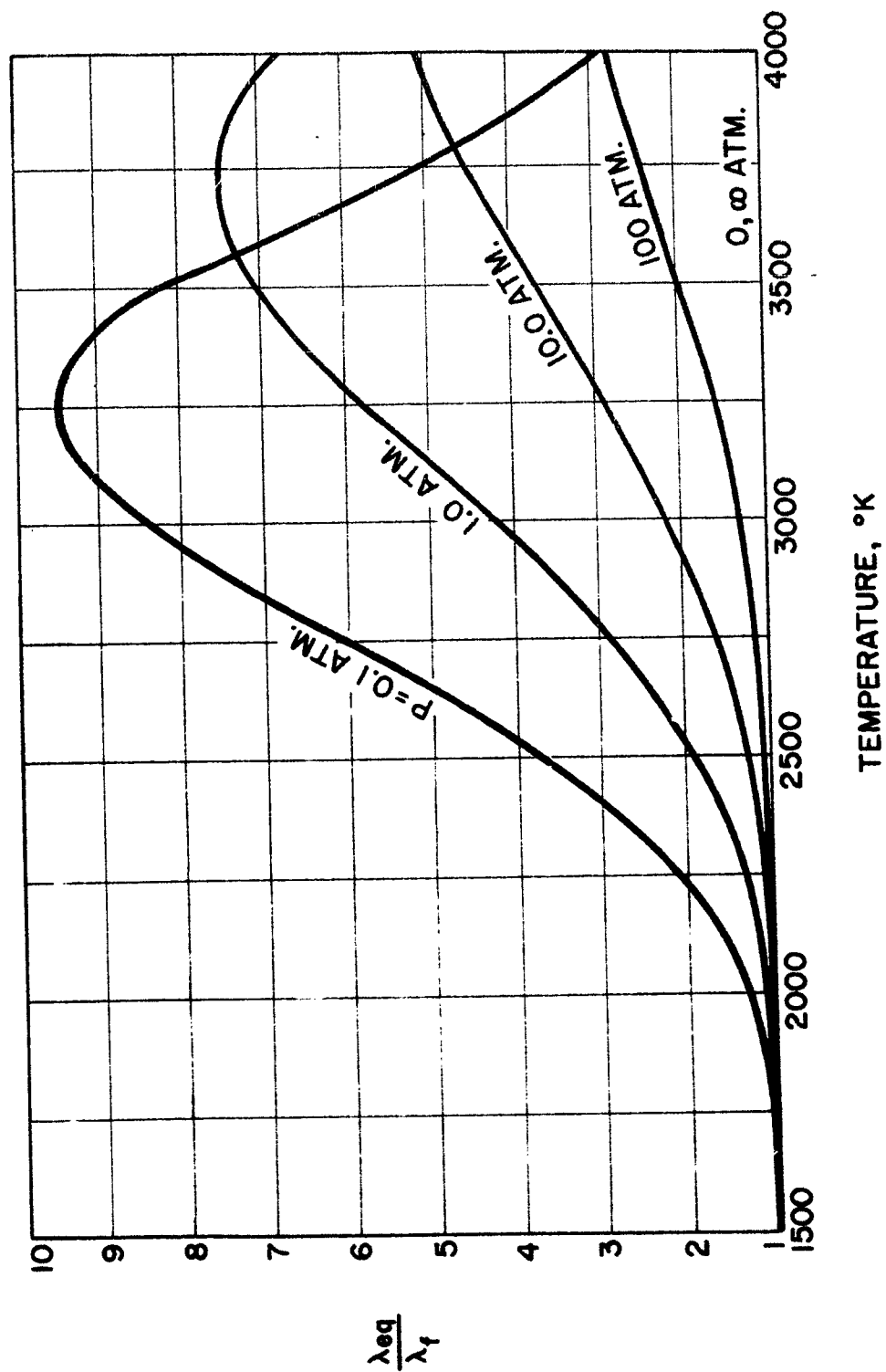


FIG. 2 EFFECT OF DISSOCIATION ON THE HEAT CONDUCTIVITY  
OF EQUILIBRIUM HYDROGEN

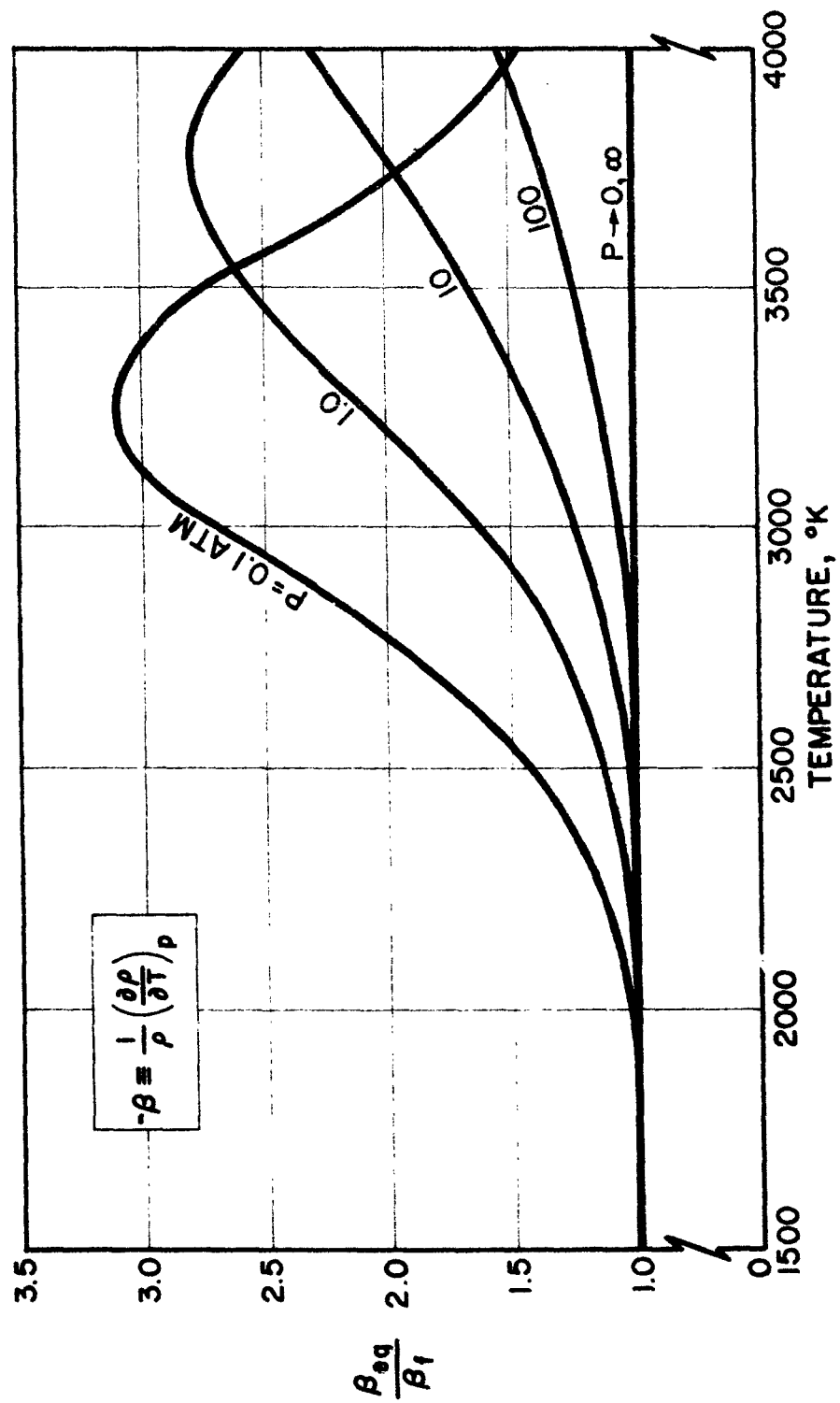


FIG. 3 EFFECT OF DISSOCIATION ON THE THERMAL EXPANSION  
COEFFICIENT OF EQUILIBRIUM HYDROGEN

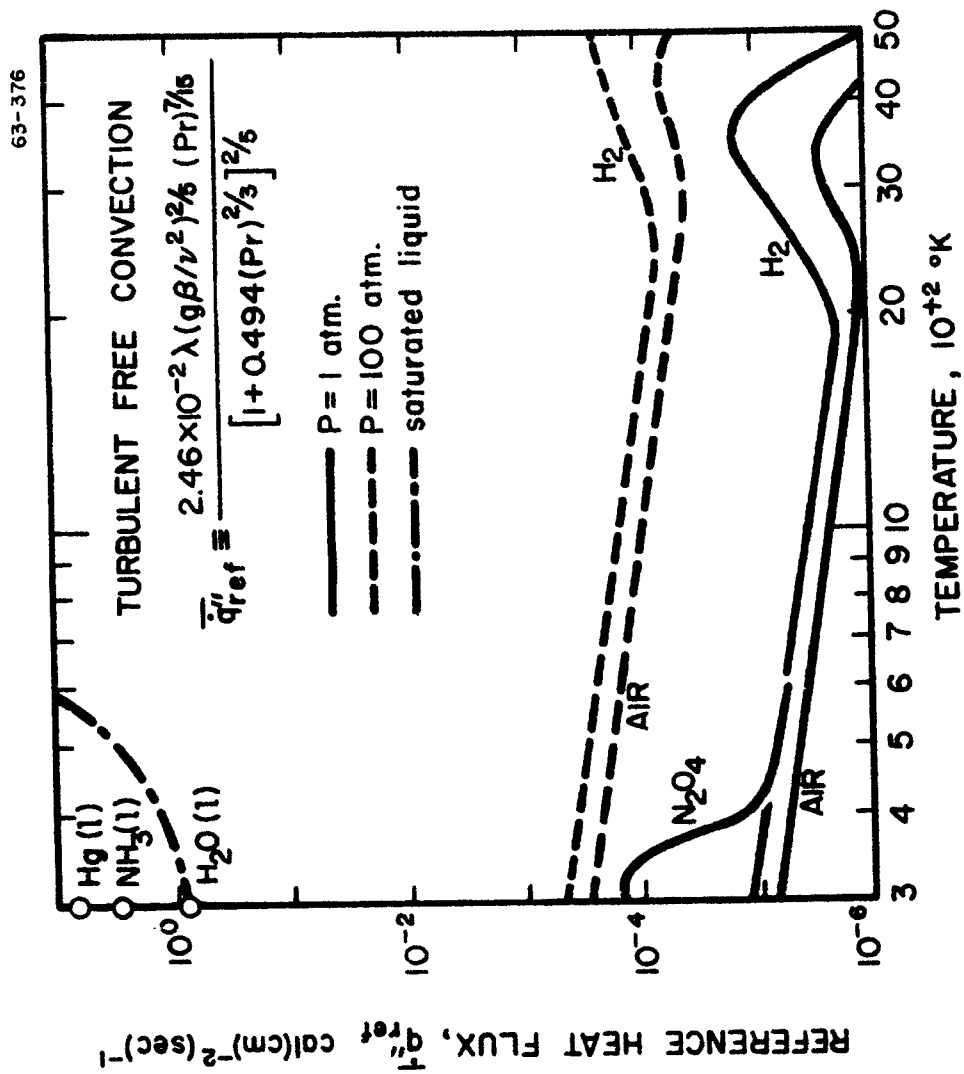


FIG. 4 COMPARISON OF LIQUIDS WITH DISSOCIATING GASES  
AS NATURAL CONVECTION COOLANTS